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Life cycle cost analysis of fuel ethanol produced from cassava in Thailand

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Abstract
Background, aim, and scope As a net oil importer, Thailand has a special interest in the development of biofuels, especially ethanol. At present, ethanol in the country is mainly a fermentation/distillery product of cane molasses, but cassava holds superior potential for the fuel. This study aims to assess the economics of cassava-based ethanol as an alternative transportation fuel in Thailand. The scope of the study includes the cassava cultivation/processing, the conversion to ethanol, the distribution of the fuel, and all transportation activities taking place within the system boundary.
Materials and methods The life cycle cost assessment carried out follows three interrelated phases: data inventory, data analysis, and interpretation. The functional unit for the comparison between ethanol and gasoline is the specific distance that a car can travel on 1 L ethanol in the form of E10, a 10% ethanol blend in gasoline.
Results The results of the analysis show, despite low raw material cost compared to molasses and cane-based ethanol, that cassava ethanol is still more costly than gasoline. This high cost has put an economic barrier to commercial application, leading to different opinions about government support for ethanol in the forms of tax incentives and subsidies.
Discussion Overall, feedstock cost tends to govern ethanol's production cost, thus, making itself and its 10% blend in gasoline less competitive than gasoline for the specific conditions considered. However, this situation can also be improved by appropriate measures, as discussed later.
Conclusions To make ethanol cost-competitive with gasoline, the first possible measure is a combination of increasing crop yield and decreasing farming costs (chemical purchase and application, planting, and land preparation) so as to make a 47% reduction in the cost per tonne of cassava. This is modeled by a sensitivity analysis for the cost in the farming phase. In the industrial phase of the fuel production cycle, utilization of co-products and substitution of rice husk for bunker oil as process energy tend to reduce 62% of the price gap between ethanol and gasoline. The remaining 38% price gap can be eliminated with a 16% cut of raw material (cassava) cost, which is more practical than a 47% where no savings options in ethanol conversion phase are taken into account.
Recommendations and perspectives The life cycle cost analysis helps identify the key areas in the ethanol production cycle where changes are required to improve cost performance. Including social aspects in an LCC analysis may make the results more favorable for ethanol.

Keywords Cassava ethanol · Life cycle cost · Renewable resources · Social aspects · Thailand · Transportation

1 Background, aim, and scope

Thailand is considered a net significant oil importer in the world. The ratio of the country's crude oil import to crude consumption stands at a high level (63% in 2006). Oil consumption costs the country a huge amount of foreign currency via oil import bills at about US$ 22 billion a year (DEDE 2007). Also associated with it is the growing

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problem of environmental degradation. In that context, domestically produced ethanol has emerged as a potential substitute for gasoline, effective in fossil energy savings and greenhouse gas (GHG) mitigation (Nguyen et al. 2007).

Though the promotion of ethanol started in Thailand about 20–30 years ago, significant production and use has only been in place since 2006. With the government's biofuel policy, ethanol is being distributed to consumers in the form of E10, a mixture of gasoline and ethanol at a ratio of 9:1. Quite confident about abundant sources of raw materials for ethanol production, the Thai government has launched a project to replace gasoline with E10 nationwide in the years ahead. As a step forward, E20 fuel (20% blend of ethanol in gasoline) is also available now in Thailand and some companies have started producing flex-fuel cars that can run on the blend (Navarro 2008). Ethanol can be made from a wide spectrum of agricultural commodities, of which sugar cane, cane molasses, and cassava are of importance in Thailand. At present, ethanol in the country is mainly produced from molasses. However, the main disadvantage of molasses-based ethanol as well as cane-based ethanol lies in the seasonal availability of feedstock. In addition to all year round availability, potentially low raw material cost (Nguyen et al. 2007) makes cassava an important option in utilization for fuel ethanol.

Life cycle energy and environmental impact of ethanol from cassava and cane molasses in Thailand have already been evaluated (Nguyen and Gheewala 2008a, b). However, life cycle cost analysis of ethanol from either feedstock has not yet been performed. The focus of this study is thus on the costs of producing ethanol from cassava, in comparison with gasoline, based on a life cycle approach. At present, it seems that without government subsidies ethanol cannot compete with gasoline in terms of price. In 2007, the average ex-refinery price of E10 was about THB 0.2 (1 USD=34 THB in 2007), a liter higher than that of its competitor, unleaded gasoline, with an octane rating of 95, hereafter referred to as gasoline (EPPO 2007a). Improvement measures in both farming phase and fuel conversion phase would enhance ethanol's potential to substitute gasoline in the long term. In addition, this renewable energy source could provide a stable market for cassava farmers to sell their product as well as contribute to environmental and energy policy goals. To assess whether an energy alternative like ethanol is feasible and practical in terms of cost, a life cycle cost (LCC) analysis is carried out. It addresses cost elements associated with all stages of the anticipated life-span of the product or service (Finnveden and Moberg 2005). The results of an LCC analysis can be used to assist decision-makers to select the best option among competing alternatives. Furthermore, the cost breakdown reveals specific areas where advanced technology and/or strategic policy could yield improvements, removing economic barriers and public controversy upon government support for ethanol via subsidies, tax incentives, etc. Well aware of the advantage of such an analysis tool, studies with a comparable method have been performed (Zhou et al. 2007; Zhang et al. 2003). Apart from private production costs or market prices, marginal social benefits of biofuels are the subject of on-going research nowadays to inform policy makers whether subsidies/tax incentives are justified for social reasons (Brännlund and Kriström 2001; Schrooten et al. 2006).

2 Life cycle cost (LCC) analysis

2.1 Ethanol fuel life cycle and functional unit

The scope of the LCC analysis includes the cassava cultivation/processing, the conversion to ethanol, the distribution of the fuel, and all transportation activities taking place within the system boundary. Figure 1 shows the major operations included in the boundary of the ethanol life cycle for conducting the detailed cost analysis. At each stage in the fuel life cycle, the expenses include materials, energy (fuel, electricity), labor, transportation, depreciation of fixed assets, maintenance, and miscellaneous cost. Farm machinery hiring and profit margin are the other cost components. The final cost of cassava ethanol, hereafter referred to as ethanol, is the sum of all of the mentioned process costs and values.

Cassava cultivation Well known for its tolerance/resistance to drought and insects/pests, cassava does not require irrigation and insecticide/pesticide application in general. Weeding is required during the first few months until the cassava plants develop shade large enough to compete for sunlight. The direct farm inputs thus include stem cuttings, diesel fuel, labor, fertilizers, and herbicides. As shown in Fig. 1, the steps involved in this stage are land preparation, planting, crop maintenance (fertilization, weed control), and harvesting including loading.

Land preparation for cassava cultivation in Thailand is done by diesel tractors; most farmers apply plowing two to three times with three-disc plow, seven-disc plow, four-disc plow and/or ridging. Land preparation is followed by new crop planting. In general, cassava is propagated vegetatively through stem cuttings prepared from the residual stems left after roots are separated at harvest. Normally, stem cuttings preparation and planting take place at the same site, which is good in terms of saving fuel and labor costs for transportation, loading, and unloading. Manual planting is a common practice in Thailand since it does not consume much labor here, about 1.5 man-days/rai ('rai' is the Thai measurement unit for land area; 1 rai=0.16 ha). For crop

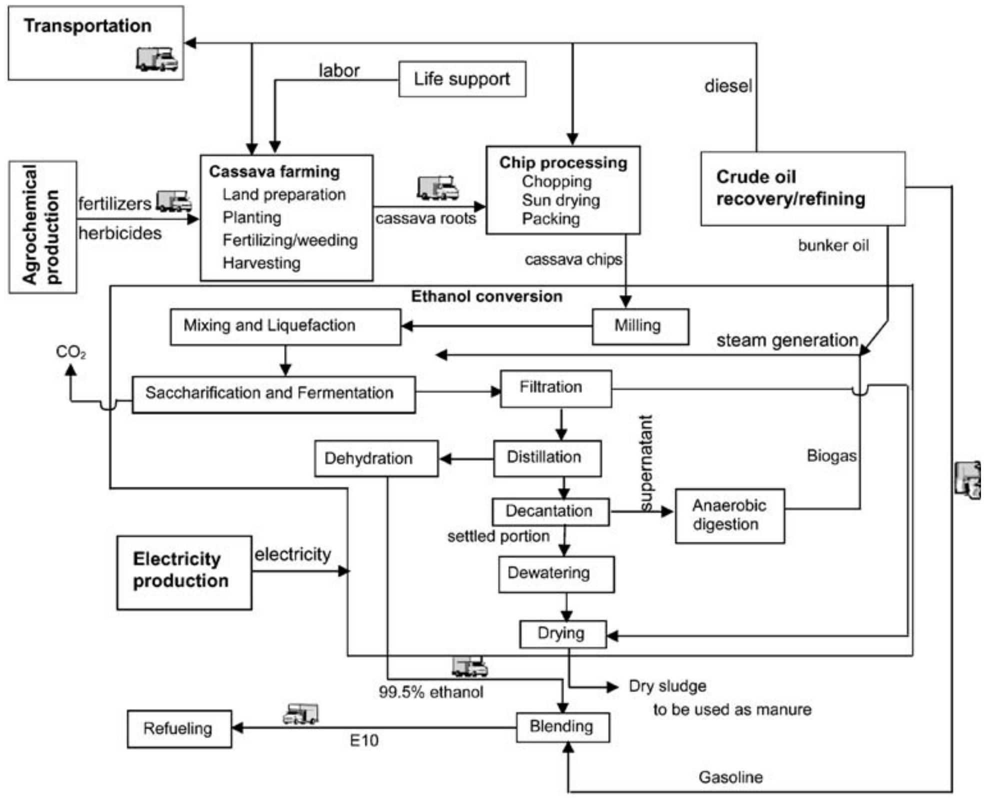

Fig. 1 Flow chart of cassava-based E10 production process

maintenance, commercial fertilizers and locally-prepared manure are the two types of materials farmers use to improve soil fertility/physical conditions. Weeding is carried out by hand, herbicides and/or small tractors. Cassava can be harvested either manually or mechanically; in Thailand manual harvest is more usual, though it is considered more labor-intensive, amounting to 3.2–6.4 man-days/rai (Howeler 2000). In the dry season, mould-board ploughs may be used to make manual digging less arduous.

Cassava processing Cassava processed into dried chips are considered more suitable for ethanol production than fresh roots in terms of storage duration, 8 months (FAO/IFAD 2004) versus 2–3 days (DEDE 2004). Roots transported to processing plants or directly to ethanol plants are loaded into the hopper of the chopping machine by tractor. After roots are chopped into small pieces or chips, they are sun-dried on a large cement floor. A tractor, with a rake attached, is used to turn the chips several times per day (Sriroth et al. 2000; Witriyatornpan 2006). After 2 to 3 days, the dry chips are ready for storage as raw material for ethanol production.

Ethanol conversion As shown in Fig. 1, the segment includes numerous steps, whereby the major ones are mixing and liquefaction, saccharification and fermentation, and distillation/dehydration. Bunker oil bills and electricity bills make energy costs of ethanol plant operation. In order to reduce ethanol cost so that it can compete with gasoline, it is necessary that all of its by-products are sustainably utilized. The solids contained in the slop supernatant separated from stillage can be utilized for energy via biogas generation, whereas the settled portion from the whole process is recommended to be used as manure/soil conditioner in nearby cassava farms (Ploypatarapinyo and Klinsukont 1987). The carbon dioxide by-product evolved from the fermentation process can be collected, purified and transformed for use in coolant, soft drink, soda, dry ice, and fire extinguisher industries (DEDE 2004).

In this study, the functional unit chosen to compare ethanol and gasoline is the specific distance that a car can travel on one liter ethanol. From fuel economy of E10 and gasoline cars in Thailand, Nguyen et al. (2007) have derived that 1 L ethanol (in the form of E10) is equal to 0.89 L gasoline.

2.2 Data collection

2.2.1 Cassava farming cost

The Thai government has approved the construction of six cassava ethanol plants in the north-eastern region, with a total output of 1.15 million liters (ML) per day in 2007–2008 (Sukphisal 2005). Of this output, 0.75 ML would be contributed by two ethanol plants located in Nakhon Ratchasima, which is the top cassava-producing province in Thailand (OAE 2006).

Cassava farming costs were collected on-site in this province. The overall cost is an aggregation of various cost components which can be categorized into five groups as follows.

1. Land preparation, including costs of fuel, hiring tractors and drivers
2. Hand planting, including costs of planting materials (cassava stems)
3. Chemical (fertilizers, herbicides) purchase and application
4. Harvesting/loading
5. Transportation of chemicals, stem cuttings and harvest

2.2.2 Ethanol conversion/distribution cost

The detailed cost breakdown for ethanol production from cassava was adapted from the two estimates prepared by the research team at the Cassava and Starch Technology Research Unit (CSTRU), Bangkok, Thailand (Ronjnaridpiched 2003; CSTRU 2007, personal communication). Up to this point, the cost of ethanol (termed ex-distillery price) is contributed by (1) raw material (i.e., cassava roots), (2) utilities (energy cost), (3) chemicals, (4) repair and maintenance, (5) insurance, (6) wages and salary, (7) depreciation, (8) fiscal charges, (9) selling expenses, (10) miscellaneous, and (11) profit margin. Adding transportation/distribution cost to ethanol ex-distillery price results in ethanol ex-refinery price. To estimate transport costs, assumptions about transport of cassava from farms to factories and ethanol from factories to oil refineries were made, as shown in Table 1.

3 Results and discussions

3.1 LCC analysis

3.1.1 Cassava farming

The production costs of cassava roots including transportation from the farms to ethanol factories are in the range of THB 1,110 to 1,340 a tonne. Selling their product to ethanol plants with the market price set by the government, at THB 1,500 a tonne (Daily Times 2007), farmers get an average profit of about THB 290 a tonne. A detailed breakdown of the average cost of THB 1,210 a tonne is shown in Fig. 2.

Table 1 Assumptions about transport activities for estimating transport cost in ethanol system

	Transport facility	Capacity (t)	Average distance, one way (km)
Cassava	Diesel truck	15–20	100
Ethanol	Diesel truck	10–12	150

3.1.2 Ethanol conversion

The production cost of cassava chips comprising the cost of 2.5 t of cassava roots and processing cost amounts to THB 3,833/t. This brings the cost of raw material to THB 11.51/L of ethanol produced, given a conversion rate of about 333 L of ethanol/t of cassava chips (Ronjnaridpiched et al. 2003). The cost displayed by ethanol product when it leaves the ethanol factory is termed the ex-distillery price. It represents production cost (THB 18.85/L) plus 10% of distillery profit margin (i.e., THB 1.9/L). The detailed ex-distillery cost breakdown for ethanol production from cassava is presented in Fig. 3.

Before being distributed to gas stations, ethanol is transported to oil refineries for blending with gasoline. At gas stations, the retail price of ethanol in the form of E10 is formulated as: retail price=ex-refinery price+oil fund+taxes+marketing margin+value added tax (EPPO 2007b), in which ex-refinery price is a sum of ex-distillery price and transportation/distribution cost. To encourage consumers to use E10, the Thai government provides fuel subsidies and tax incentives that make E10 cheaper than gasoline. Thus, a fair comparison between ethanol and gasoline should be based on their ex-refinery prices rather than retail or pump prices.

Transportation cost for ethanol from ethanol factories to oil refineries was estimated based on the assumptions presented in Table 1. Adding this cost to ethanol ex-distillery cost results in the ethanol ex-refinery price of THB 21 a liter. As of 2007, ex-refinery prices (i.e., the prices before all forms of oil fund levy/tax package, marketing margin and value added tax are added to make retail prices) for gasoline and E10 averaged THB 18.35 and 18.52 a liter, respectively, giving a price gap of only THB 0.17 on a per-liter basis (EPPO 2007a). However, when the difference in fuel economy between gasoline and E10 car is taken into account, the gap increases to THB 0.38. For E10 to be competitive with gasoline, the ethanol ex-refinery price has to be reduced to THB 16.33 a liter, given that one liter ethanol (in the form of E10) is equal to 0.89 L gasoline (Nguyen et al. 2007). As compared to the ex-refinery price of THB 21 a liter, there exists a gap of THB 4.67 a liter. The advantage of an LCC analysis is to provide a whole cost structure of the ethanol life cycle. From such an analysis, one can identify specific areas where technological innovation or strategic policy is needed to make such an energy alternative feasible in terms of cost. As shown in Fig. 3, feedstock price is the dominant cost factor in ethanol production; it represents 56% of the ethanol ex-distillery cost, whereas ethanol conversion contributes about 44%. A reduction in cassava price would be one possible way to

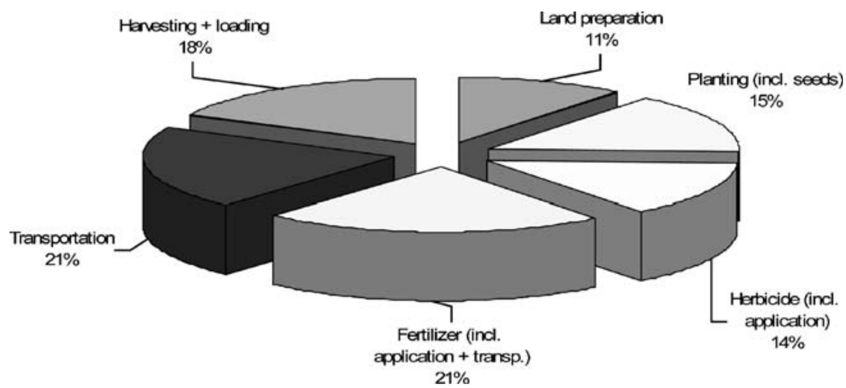

Fig. 2 Cassava cost structure

reduce ethanol production cost. In the conversion phase, utilization of ethanol by-products would help offset ethanol production cost. However, an economic analysis of by-products should be done to assess this possibility. Another option is substituting cheaper fuels for bunker oil to power the ethanol factory.

3.2 Possibilities of cost reduction

3.2.1 Farming phase

Tracing back to farming phase, to make ethanol ex-refinery price drop to THB 16.33 a liter, cassava roots should be available at a market price of no more than THB 936 a tonne. As a result, production cost for cassava has to drop to THB 646 a tonne, which corresponds to a 47% reduction, assuming that the profit for farmers is fixed at THB 290 a tonne.

If farming cost per rai remains the same, raising cassava crop yield is one option for reducing the cost per tonne of cassava. As shown in Fig. 4, the yield making the cost per tonne of cassava drop to THB 646 is more than 13 t/rai, i.e., about 3.8 times the current yield of 3.4 t/rai. In the short term, this seems neither feasible nor practical. During the past 10–12 years (1995–2006), the average annual yield of cassava in Thailand has remained the same or, in some years, increased slightly (about 5.5%; OAE 2006). Yield stagnation has resulted from soil losses due to erosion and inappropriate fertilizer application (Howeler 2000). A combination of reducing farming cost per rai (chemical purchase and application, planting and land preparation) and increasing yield would be more practical. The straight line in Fig. 4 also shows a series of different combinations of cassava yield per rai and farming cost reduction resulting in a cost per tonne of THB 646. For instance, a 50% reduction in farming cost per rai combined with a yield of 7 t/rai would be as effective as a 280% increase in crop yield alone (13 vs. 3.4 t/rai). The dissemination of a good stock of new varieties and better cultivation/harvest practices are all potential measures to make cassava-based ethanol more competitive.

3.2.2 Ethanol conversion cost

a. Substitution of rice husk for bunker oil

The pilot plant producing ethanol from cassava uses bunker oil as the main source of process energy. Fuel energy content and price (EPPO 2007b; TEI 2001; Chungsangunsit 2005; Thongrung 2007) comparison show that bunker oil costs about THB 0.44 per MJ, whereas rice husk costs only THB 0.06 per MJ. If a

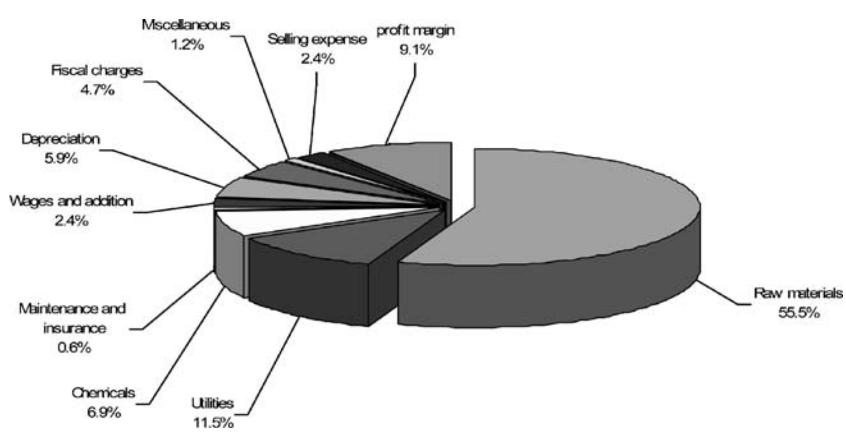

Fig. 3 Breakdown of ethanol ex-distillery price

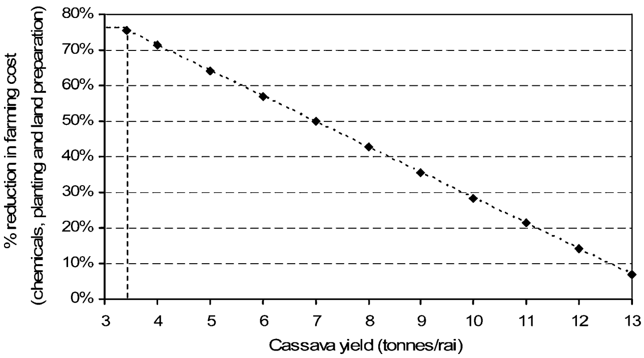

Fig. 4 Break-point cassava cost (THB 646/t) in varying cassava yield and % reduction in farming cost per rai

nearby source of rice husk is available (assuming a one-way transport distance of 50 km), its substitution for bunker oil would save THB 2/L of ethanol produced.

b. Utilization of ethanol by-products
CO_2: there are several ways an ethanol plant can collaborate with CO_2 customers as a supplier of untreated or purified CO_2 products. The more finished the CO_2 by-product leaving the ethanol factories, the larger will be the value added; whereby the processing costs as well as capital and operating costs will also increase. The simplest way is collecting, compressing, and selling CO_2 to nearby processors which accept the product with relatively low purity requirements, e.g. soda manufacturing facilities and enhanced oil recovery projects. A modest selling price for 'raw CO_2' is estimated between \$4 and \$15/tonne (Advanced Cryogenics Limited 2004). For every kg of ethanol produced, approximately one kg (exactly 0.957 kg) of CO_2 can be generated stoichiometrically. Thus, per liter of ethanol, about THB 0.3 can be salvaged from CO_2.
Manure: 1 t of cassava chips passing the ethanol conversion process can produce about 84–89 kg sludge having 10% moisture content after dewatering and drying (Ronjnaridpiched et al. 2003). This sludge, having a value as a good soil conditioner, can be sold to cassava farmers (Ploypatarapinyo and Klinsukont 1987) at a low price (THB 2.5/kg versus THB 12/kg commercial fertilizer). The process heat required for sludge drying could be derived from rice husk. Among various biomass-based energy resources relevant to Thailand, rice husk ranks second after bagasse regarding supply outputs (NEPO 2000). The contribution of manure to 1 L of ethanol, THB 0.6, is obtained by subtracting drying cost from manure selling price.

The combination of the two options of utilization of ethanol by-products and substitution of rice husk for bunker oil leads to a final ethanol cost (ex-refinery price) of THB 17.88 a liter. In order to make the two options feasible considering transport cost, it is expected that an integrated industrial zone comprising ethanol distilleries, rice mills and CO_2 processors is established.

The THB 17.88 a liter ethanol as per the estimate above is still THB 1.55 in excess of the reference price. This excess would be fully compensated by a decrease in raw material cost to THB 10.10 a liter which implies that cassava roots should be available at a market price of no more than THB 1,312 a tonne. As a result, production cost for cassava farming has to drop to THB 1,022 a tonne (i.e., 16% reduction). This reduction, again, could result from a series of different combinations of cassava yield and farming cost reduction per rai (Fig. 5). If seen along with Fig. 4, it can be concluded that a combination of all options in farming phase and ethanol conversion phase would be more practical and feasible than either option alone. With the current yield (3.4 t/rai), farming cost per rai needs to be reduced by 25% (instead of 76% as used in Fig. 4). Along the straight line in Fig. 5 are other combinations of crop yield and % reduction in farming cost, e.g. 4.1 t/rai and 10% reduction, 4.6 t/rai and 0% reduction, etc.

Table 2 shows a summary of various possibilities of ethanol cost reduction.

3.3 Environmental and social aspects

3.3.1 Environmental impact

The life cycle assessment of cassava ethanol in Thailand has been conducted by Nguyen and Gheewala (2008a). Energy and environmental impacts of ethanol (in the form of E10) and gasoline have been examined at comparable levels. In the study, it was found that using cassava-based E10 substituting for gasoline results in a modest reduction in fossil energy use, petroleum use, GHG emissions, acidification, and nutrient enrichment.

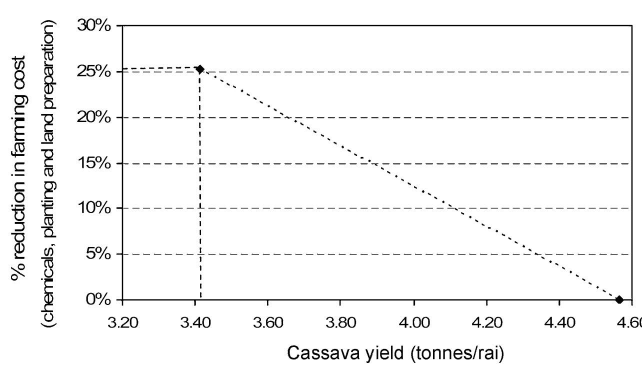

Fig. 5 Break-point cassava cost (THB 1,022/t) in varying cassava yield and % reduction in farming cost per rai

Table 2 Ethanol cost reduction opportunities

Items	Current cost, THB/L	Cassava cost: THB 646 a tonne	Options in ethanol conversion phase	Combined option
Feedstock	11.51	7.28	11.51	10.10
Ethanol conversion	7.34	7.34	5.34	5.34
Chemicals	1.43		1.43	
Utilities (energy costs)	2.38		0.38	
Repair and maintenance	0.06		0.06	
Insurance	0.06		0.06	
Wage and salary	0.49		0.49	
Depreciation	1.22		1.22	
Fiscal charges	0.97		0.97	
Selling expense	0.49		0.49	
Miscellaneous	0.24		0.24	
Total production cost	18.85	14.62	16.85	15.44
Profit margin	1.90	1.46	1.68	1.54
Ex-distillery price	20.75	16.08	18.53	16.98
Ethanol transportation/distribution	0.25	0.25	0.25	0.25
Ex-refinery price	21.00	16.33	18.78	17.23
Price gap with gasoline (1 L EtOH # 0.89 L gasoline)	4.67	0	2.45	0.90
Co-product utilization				
CO_2			–0.3	–0.3
Manure			–0.6	–0.6
Ex-refinery price			17.88	16.33
Price gap with gasoline (1 L EtOH # 0.89 L gasoline)			1.55	0

3.3.2 Marginal benefits from petroleum energy and GHG savings

The results from the reference mentioned above can be used to evaluate oil import reduction benefit of ethanol. Using the figure of petroleum energy savings resulting from the substitution of 1 L ethanol for 0.89 L gasoline, a rough estimation can be made that the production and use of 1 L ethanol would reduce oil use by 0.47 kg. In the context of lacking conceptual guidelines/framework for oil use savings characterization, some monetary scheme to quantify such external benefit can be applied. EPS (Environmental Priority Strategies in product design) is one of the many different valuation models well known for its simplicity and flexibility in supporting product designers and developers in comparing environmental impacts among alternatives (Dimitrios and Aristomlenis 2005). Using the default index for oil use from the EPS model (Steen 1999), multiplied by adjustment factor for Thailand (NEPO/DANCED 1998), one can convert the savings mentioned above into an external benefit of THB 3.0. The benefit increases to THB 3.8 if bunker oil used in ethanol conversion is substituted by rice husk.

One of the major rationales for the promotion of biofuels is their low GHG emissions compared to fossil fuels. The study by Nguyen and Gheewala (2008a) enables one to quantify not only oil savings, but also GHG savings from the use of cassava ethanol as a gasoline substitute in Thailand. GHG savings from 1 L ethanol substituting gasoline in transportation amount to roughly 1.6 kg CO_2 eq. The figure increases to 2.3 kg with the substitution of rice husk for bunker oil used in ethanol conversion. The savings correspond to external benefits of THB 0.3 and 0.4 a liter, respectively, using the lowest CERs (Certified Emission Reductions) rate for Thailand, US\$5/t CO_2 eq (Kalayanamitr and Tirangkura 2007).

Table 3 Farmers' income under different yields

	3.4 t/rai	4.5 t/rai	5.0 t/rai
Income (THB/rai/month)	99	131	145

Thus, marginal social benefits of ethanol with respect to fossil oil energy and GHG savings upon substituting for gasoline add up to THB 3.3–4.2 a liter depending on whether or not rice husk is substituted for bunker oil. Including these external benefits in the ethanol price would reduce the gap with gasoline by 70% (from THB 4.7 down to THB 1.4 after subtracting THB 3.3) or even reverse it in favor of ethanol (from THB +2.5 to THB –1.7 after subtracting THB 4.2).

3.3.3 *Stabilization of farmers' incomes*

One of the important social aspects of ethanol is a stabilization of farmers' incomes. A stable ethanol market for cassava once set up would benefit a great number of cassava farmers in rural Thailand. Table 3 summarizes farmers' income per rai per month under different yields. It is simple to multiply the values in the table by the area of land that a farmer owns to estimate his or her monthly income. For instance, a small cassava farmer owning 40 rai can earn THB 3,960, 5,200, 5,800 a month depending on the yield potentially achieved of 3.4, 4.5, 5.0 t/rai respectively. Fortunately, living expenses in rural Thailand are not too high so that small cassava farmers can survive on these modest incomes.

3.3.4 *Profit for farmers/ethanol producers and rural employment stabilization*

Per liter of ethanol produced, farmers get profit: 290×2.5/333=2.2 THB, and ethanol producers are assumed to get: THB 1.5–1.9 (10% of production cost). With the government target of 3.4 ML ethanol a day, farmers could make a profit of THB 2,220,720,721 (US$ 65,315,315), and ethanol producers could earn THB 1,530,000,000–1,938,000,000 (US$ 45,000,0000–57,000,000) a year. In terms of rural employment, the production scale can stabilize 21,165,563 workdays for cassava farm laborers per year estimated from the equation below.

$$\begin{aligned}\text{Labor need(days/year)} &= \text{labor use rate (man} - \text{days/rai)}\\ &\times \text{ethanol yield } (\text{L/rai})^{-1}\\ &\times \text{ethanol production scale}\\ &\quad (\text{L/year})\end{aligned}$$

where

$$\text{labor use rate} = 9.4\,\text{man} - \text{days/rai}$$

$$\begin{aligned}\text{Ethanol yield} &= \text{ethanol conversion rate (L/t chips)}\\ &\times \text{chip conversion rate(t/t roots)}\\ &\times \text{root yield(t/rai)}\\ &= 333 \times 0.4 \times 3.4\\ &= 453\text{L/rai}\end{aligned}$$

$$\begin{aligned}\text{Ethanol production scale} &= \text{daily production capacity (L/day)}\\ &\times \text{working days/year}\\ &= 3,400,000 \times 300\\ &= 1,020,000,000\,\text{L/year}\end{aligned}$$

The results of the calculation are quite informative vis-à-vis evaluating social aspects of ethanol. However, there arises the question: How could these marginal benefits be monetized and included in the market price of the fuel before making a comparison with its counterpart gasoline. Furthermore, the other two marginal benefits that also need to be quantified and included in a cost analysis of biofuels are (1) promoting proper farming practices and advanced fuel conversion technologies; and (2) supporting domestic markets for agricultural commodities to substitute for foreign oil. Monetization of social benefits of biofuels is clearly an important area for future research.

4 Conclusions and recommendations

A comprehensive life cycle cost and further social aspect analysis provide relevant information for policy makers since they allow a fair comparison between the two fuel alternatives. The case study of fuel ethanol from cassava in Thailand has led to the following conclusions:

More than half of ethanol production costs are contributed by feedstock price. A possible measure to make ethanol competitive to gasoline is a combination of increasing crop yield and decreasing farming costs (chemical purchase and application, planting and land preparation).

Optimization of the ethanol conversion process would also contribute to the overall cost reduction notably by substituting rice husk for bunker oil as the main source of process energy and utilizing ethanol by-products (e.g., CO_2 and the settled portion separated from distilled mash). However, a life cycle analysis taking into account by-product cost savings/credits as suggested by the second option would only be valid to the extent that markets for these by-products are developed and maintained (Fu et al. 2003). Also, an integrated industrial complex comprising ethanol distilleries, rice mills and CO_2 processors should be established to ensure efficient flow of materials. This would contribute to optimizing the logistics and, hence, enhancing the overall cost-effectiveness and environmental benefits of ethanol production.

One may expect that either a decrease in ethanol production cost or an increase in gasoline price would favor ethanol over gasoline. In fact, rising oil prices would make the production cost of ethanol increase accordingly, since ethanol is still a product of an oil-based economy. The gap could effectively get narrower or even eliminated with a decrease in the costs expended in producing ethanol. More feasible and practical to reduce the cost is a combination of all options in farming phase and ethanol conversion phase. This would be achieved by a modest rate of fossil-based fuel/material inputs in ethanol production cycle brought about by appropriate farming practices and advanced ethanol conversion technologies.

Finally, yet importantly, a conventional cost estimate for bio-ethanol would not inform the public adequately about the various benefits which are difficult to quantify in monetary terms. A preliminary analysis taking into account external costs for fossil oil use and GHG emissions showed that the cost performance is substantially altered in favor of ethanol.

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